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Experiments with the assimilation of thermal profile data into a dynamical model of the Atlantic Ocean

by

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November 1994

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Summary

Results are presented from a set of integrations in which thermal profile data reported via the GTS (Global Telecommunications System) in April 1993 are assimilated into a primitive equation model of the Atlantic ocean. Statistics for the fit of the resulting fields to independent observations are compared with the fit of the initial states and climatological fields. Some problems with the model fields and the response of the barotropic streamfunction to the observations in these integrations are identified and remedies proposed. Results from integrations assimilating data delivered by the GTS or data prepared by the NMC (National Meteorological Center) from July to September 1993 are then presented and discussed.

1. Introduction

Considerable progress in the assimilation of thermal measurements into ocean general circulation models has been achieved recently for the global ocean by Clancy et al (1992) and for the tropical Pacific by Leetmaa (1993) and Smith et al. (1991) . A system to assimilate data into a primitive equation ocean model has now been developed at the Met. Office (UKMO). This system was run by the FOAM (Forecasting Ocean Atmosphere Model) group in near real-time between December 1993 and Februay 1994 (Foreman et al. 1994).

This paper discusses results from two sets of integrations performed with models of the Atlantic and Arctic Oceans north of 30 °S. One set consists of many integrations assimilating one month of BATHY data reported over the GTS in April 1993. The second set consists of several integrations in which three months of BATHY and TESAC data reported in July-September 1993 are assimilated. The main aims of these integrations are:

(1) to assess the overall performance of the system

(2) to understand the response of the system to some of the processing steps and to changes in the most important assimilation parameters and to make sure that these parameters are given appropriate or realistic values

(3) to check for unexpected responses to the data being assimilated

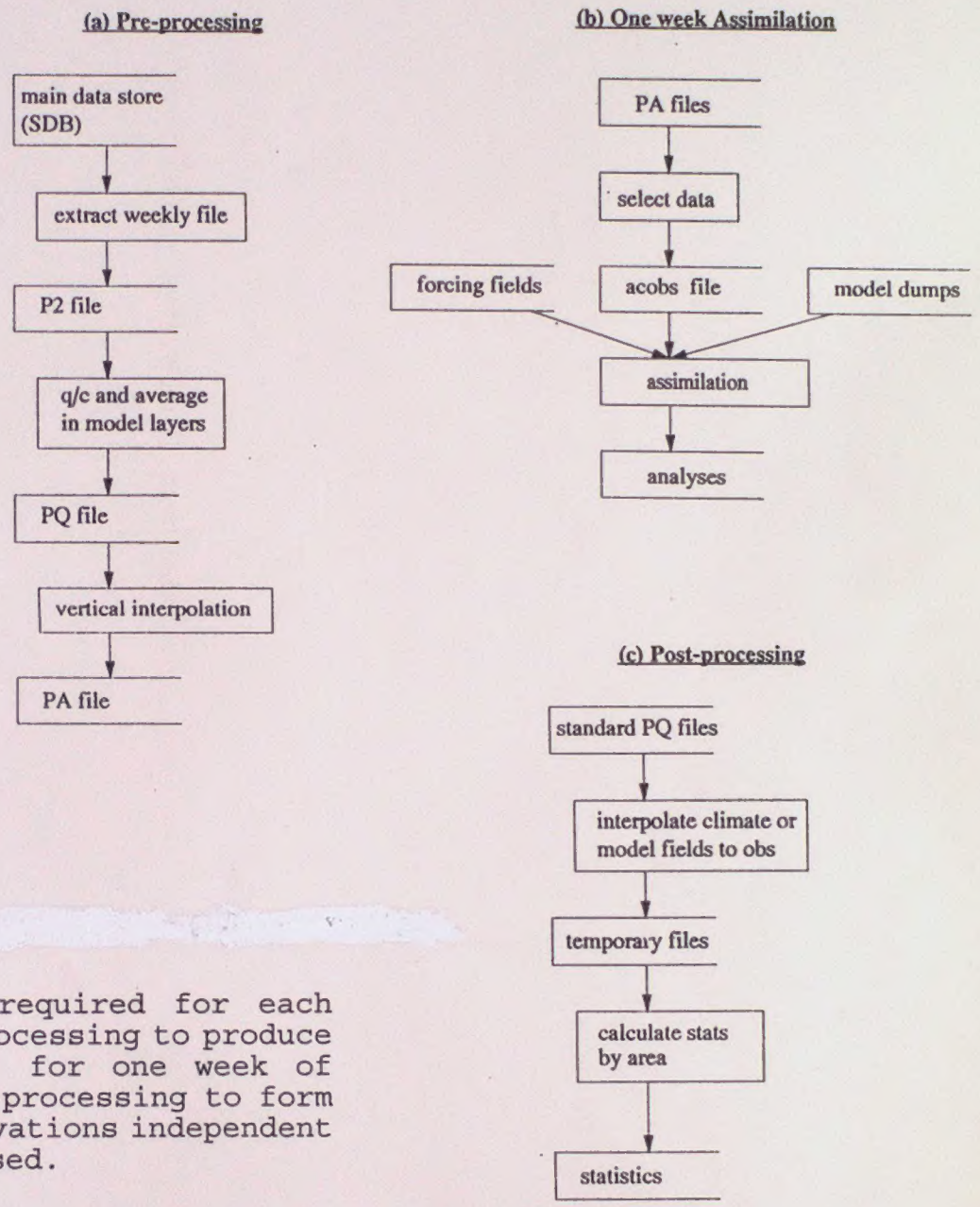


Figure 1 Processing required for each integration (a) pre-processing to produce a single PA file (b) for one week of assimilation (c) post-processing to form statistics using observations independent of those previously used.

(4) to order priorities for future development.

The paper is organised as follows. Section 2 describes the processing performed for each integration. Section 3 presents and discusses the results: sub-section 3.1 illustrates the distribution of the observations used; 3.2 presents results from the integrations using April data; the main problems revealed by these integrations in the model and the analysis components are discussed in sub-sections 3.3 and 3.4 respectively; finally 3.5 presents results from the July -September integrations. Section 4 provides a summary and outlines work in progress on the development of the system. Bell (1994) gives a more detailed account of the material in section 2 and sub-sections 3.1 to 3.4.

2. Description of Processing

To explain the processing involved in each integration I have split it into three parts: (a) pre-processing (b) assimilation (c) post-processing. These are depicted in figures 1 (a) to (c).

(a) Pre-processing

Observations are extracted from the main real-time data store in the Met. Office and read into what will be called a P2 file. In all integrations described each file contains data for one week.

The data are then quality controlled (q/c) and averaged vertically as follows. Potential temperature and salinity from the Levitus (1982) monthly climatology fields are interpolated to each observation location. The observations are converted to potential temperature and values differing from the climate value by more than 4 °C flagged. Values in a profile which pass this test are averaged to the nearest model levels. The resulting weekly files will be called PQ files.

Finally gaps in the vertical profiles are filled in by interpolating differences between the observation values and the climate values on the model levels vertically. The resulting files will be called PA files.

(b) Assimilation

For a one month assimilation, four weekly files are built in what will be called the acobs format. The first contains data from the corresponding week's PA file. The other files contain two weeks of data taken from the corresponding and the previous weeks' PA files.

Each assimilation starts one week before the middle of the period covered by the first extraction file (see figure 2). Data from the first acobs file is assimilated for the first 7 days. Data from the next acobs file is then assimilated for the next 7 days etc. Between finishing with one acobs file and starting with the next all model fields are output (as pp fields and model dumps).

During the assimilation, analysis steps nudging the model towards the observations are made

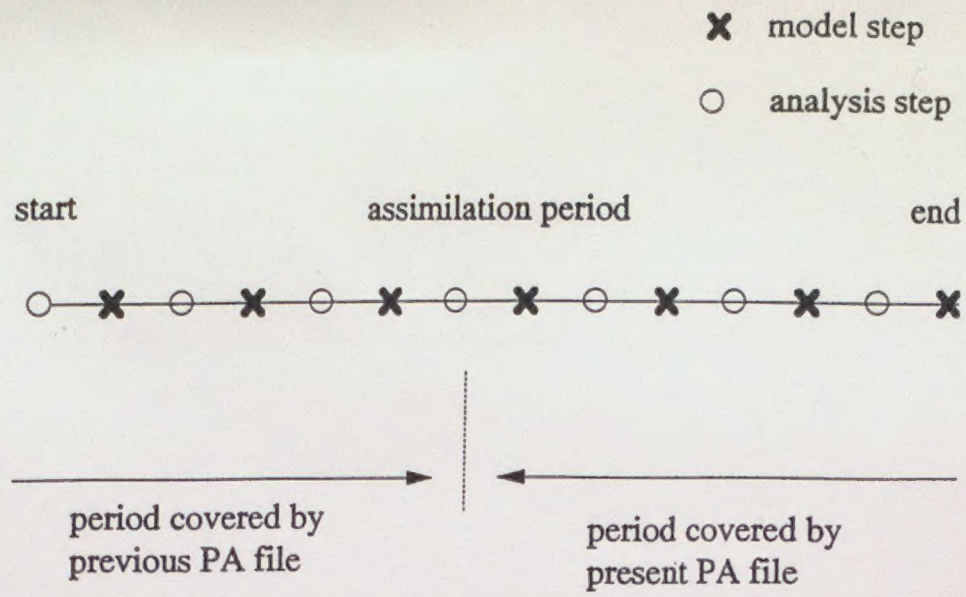


Figure 2 Interleaving of analysis and dynamical model steps during a one week assimilation and the periods covered by the present and previous PA files from which the acobs files are formed.

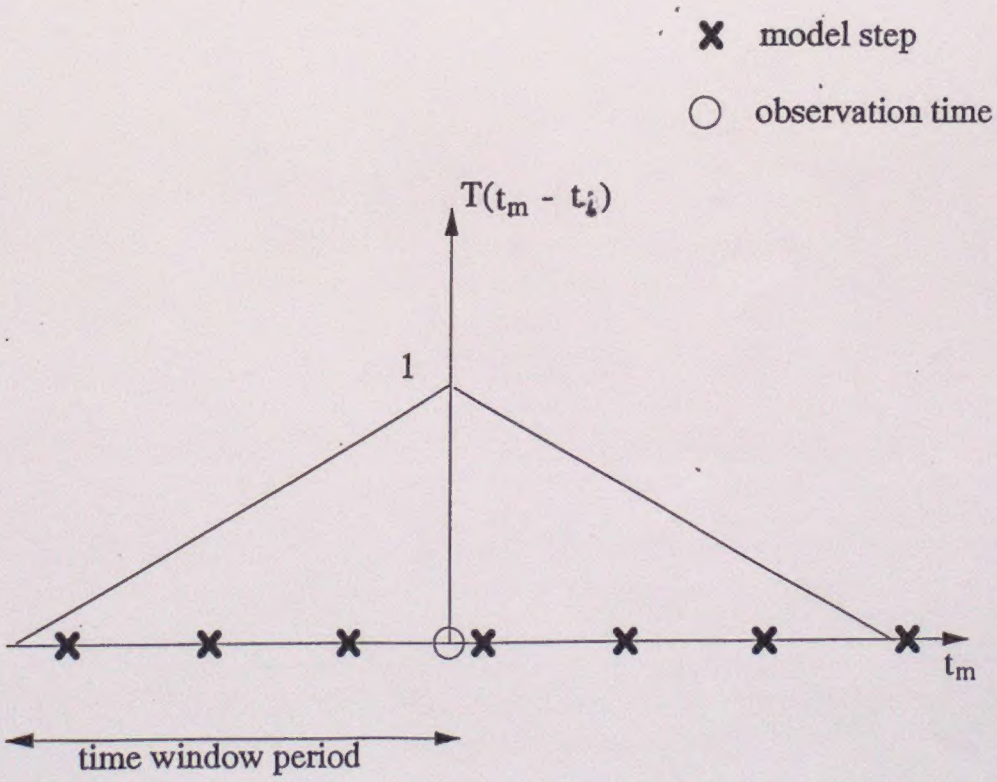


Figure 3 The time weighting factor $T(t_i-t_m)$ (sometimes called the time window) at model times t_m, for an observation valid at time t_i. $T(t_i-t_m)$ is 1 when $t_i=t_m$ and decreases linearly to zero at model times which differ from the observation time by the time period τ_m which is 5 days in the integrations discussed and the same on both sides of the observation time.

between each of the half hour model timesteps. On each model step the ocean is driven by well-known estimates of climatological fluxes and the ocean surface temperature is relaxed to that of Levitus (see Foreman et al. (1994) or Bell (1994) for more details).

On each analysis step only observations within a time window based on the current model time are used. In most integrations the weight given to an observation relative to the model field is largest when the model and observation time coincide and is decreased linearly with the time difference between the observation and model time over a time window of 5 days on each side of the observation (see figure 3).

The model potential temperature field is interpolated to each observation and the difference, the observation increment, calculated. This increment is multiplied by a nudging coefficient which is chosen to be the reciprocal of twice the number of time steps in the period covered by the window. With this choice the increments are introduced gradually and the total (i.e. time integrated) increment is about that which would be obtained by applying the full increment once.

Each of the observation increments can be thought of as an estimate of the error in the model field at that point (Rutherford 1972). This correction to the model field is spread horizontally to surrounding gridpoints using a correlation function which is (crudely) representative of the way in which model errors are estimated to be correlated. The weight given to an observation decays with the distance r from the observation by the following factors: 0.74 for r=300 km, 0.4 for r=600 km, 0.2 for r=900 km.

The baroclinic velocities in the model are incremented by velocities which are in geostrophic balance with the thermal increments which have been introduced on the analysis step. The barotropic currents are not adjusted.

(c) Post-processing

The model output from the end of each week is used as input to packages which plot out model fields. In addition the fields are interpolated to independent observations and the r.m.s. differences calculated on each model level.

The independent observations used for analyses from the end of a given week are the observations received in the next week; i.e. those in the next week's P2 file. It is important that statistics for all integrations use the same independent observations so the same PQ files are used for each integration. These files contain quality controlled observations which have been averaged to model levels but not smoothed vertically (see (a) above). Most of the observations compared against each week's analysis in this way are valid several days after the analysis time. (It would have been preferable to make 7 day forecasts from the analyses and compared them against the observations). As a guide to performance, the initial field used for the integrations, weekly fields from a control integration (in which data is not assimilated) and the monthly climate field are also compared against the observations. Only observations which can be compared against all fields are used in the statistics.

TABLE 1: Number of observations used in forming statistics for April integrations for each model level in each of the areas of the Atlantic divided by 30 °N and 30 °W

Level	Depth	NW	NE	SW	SE
1	5.00	112	208	114	114
2	15.00	22	30	6	19
3	25.00	30	35	15	43
4	35.10	30	29	34	55
5	47.85	35	59	43	78
6	67.00	44	76	84	91
7	95.75	66	102	93	92
8	138.90	55	117	105	86
9	203.70	71	143	106	96
10	301.00	84	132	98	97
11	447.05	101	142	104	102
12	666.30	95	151	73	70
13	995.55	8	42	1	0
14	1500.83	7	40	1	0
15	2116.09	0	1	0	0

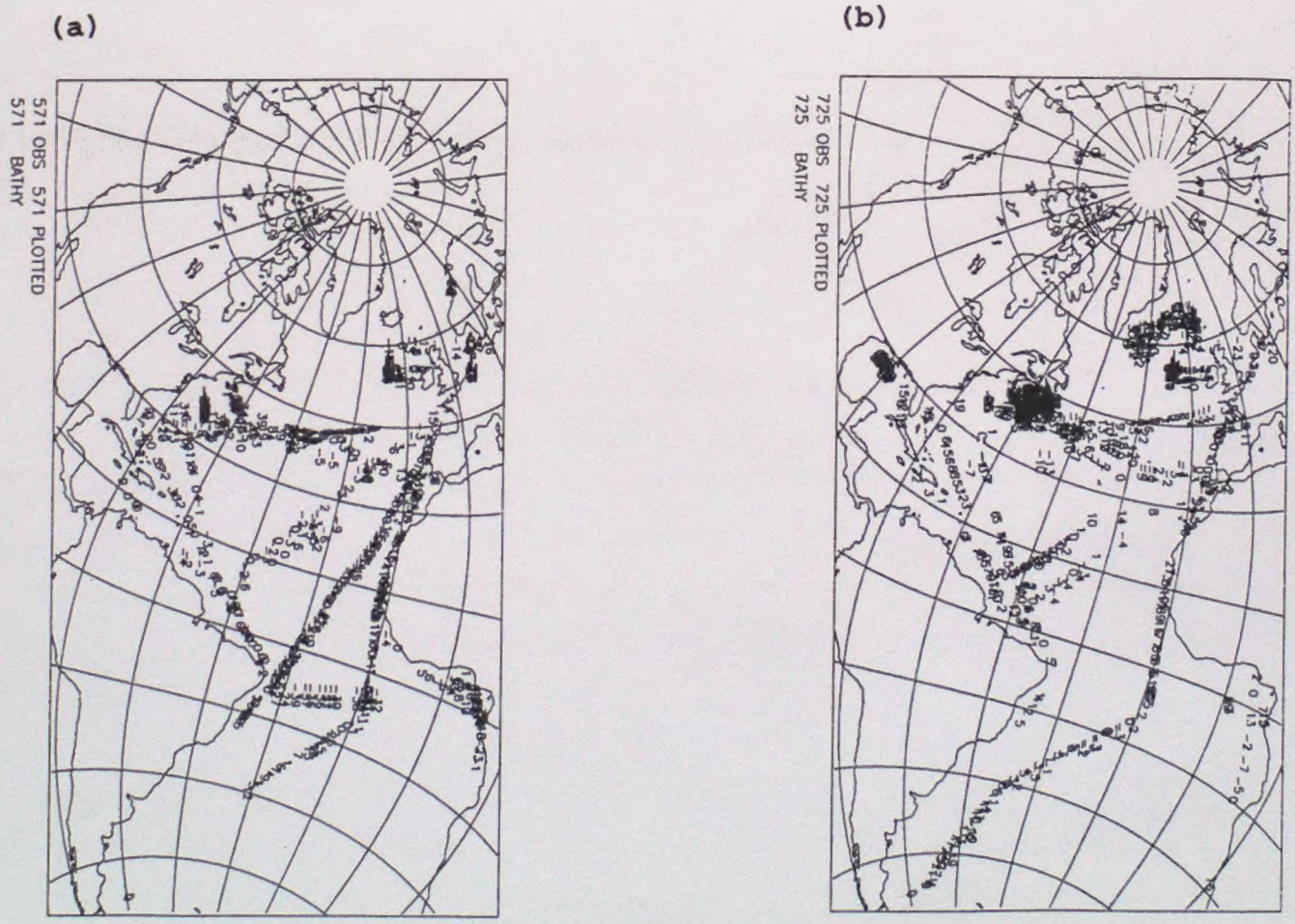


Figure 4 BATHYs reported at the surface during (a) 02 - 29 April 1993 and (b) July 30th to September 1st 1993.At each report the observed value minus the climatology (valid on 15th April) is displayed in tenths of °C.

The statistics are calculated in the four areas in the Atlantic divided by 30 °N and 30 °W. These areas basically follow Clancy et al. (1992) with intercomparison in mind. But they also divide the active west side of the North Atlantic from the quieter eastern side and the equatorial zone from the North Atlantic.

3. Results from Integrations

3.1 The distribution of the Observations

It is useful to look at the distribution of the observations used both in the horizontal and the vertical. Table 1 shows the number of BATHY observations lying within each model layer for the whole domain for the four weeks of April used to calculate statistics for that month. The number of measurements reported in layers 2 to 6 is smaller than at the surface and at greater depths. This reflects the fact that most observations are reported at significant levels and should be treated as such. The filling of gaps in the vertical performed after quality control will counteract this problem (but not in a very satisfactory way). Rather few observations occur in most areas at or below 1000 metres.

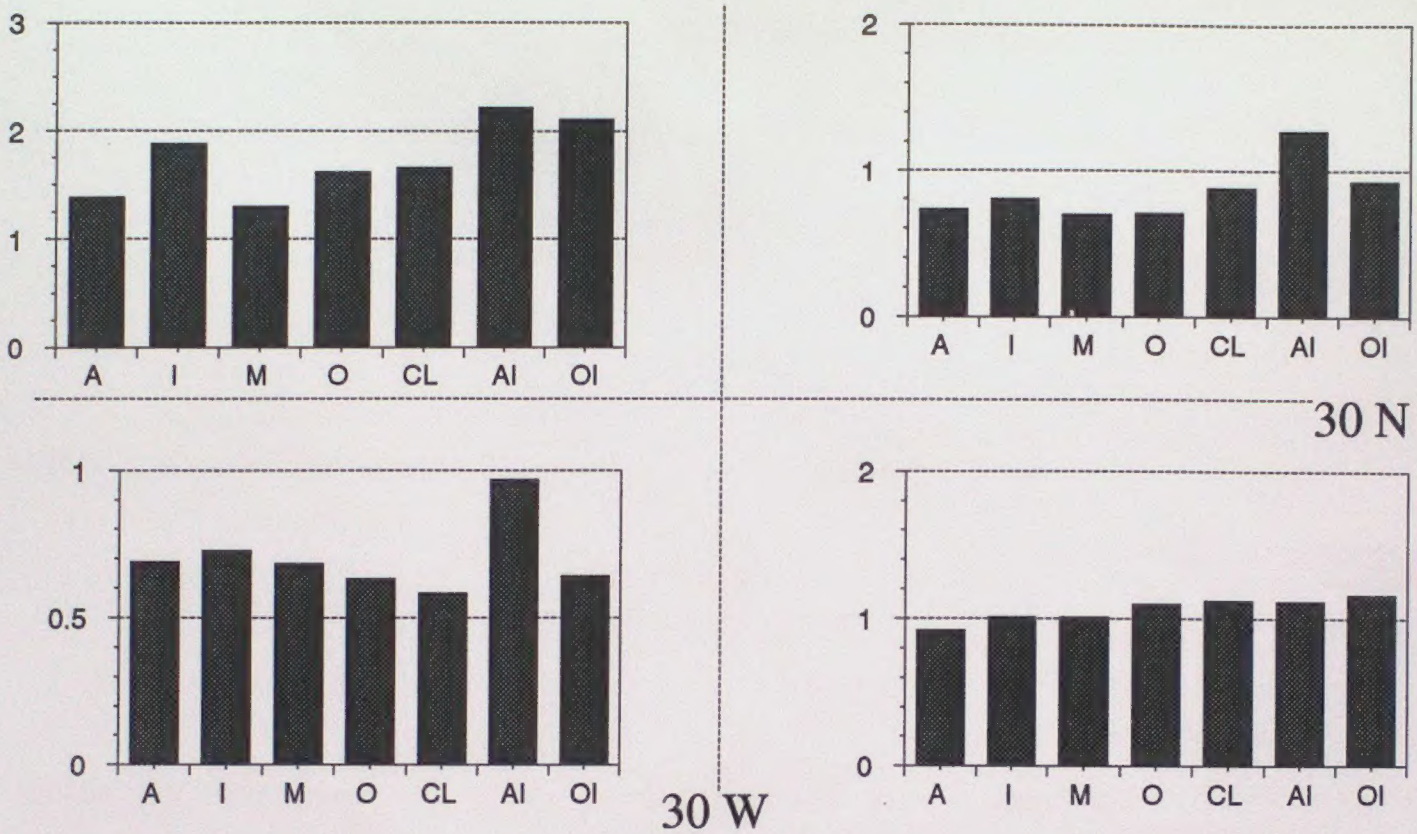
Figure 4 displays the horizontal distribution of reports at the surface in the model domain for (a) April and (b) August. The difference between the observation and the climate field (for the middle of the month) at the surface is plotted in tenths of °C for all the observations. Even in plots of a month of data, individual ship tracks are clearly visible. It is plain that there are some stations (e.g. the ocean weather ship near 55 °N, 20 °W) which report very frequently. These stations can dominate the statistics in some areas (particularly in that NE of 30 °N, 30 °W).

3.2 Results for April experiments

Results from a large number of intergrations using data from April 1993 are described in Bell (1994). Figure 5 presents results from just 4 integrations (A,M, O and I) which illustrate the sensitivity of the assimilations to the initial conditions. For these integrations, figure 5 presents the total root mean square differences between the analysis potential temperatures at the end of each of the 4 weeks of the integration and the observations reported in the next week. Values are presented for (a) the surface layer, (b) model levels 4 to 6 (35 to 67 metre depth) combined and (c) levels 9 and 10 (200 and 300 metres depth) combined. Also plotted are the corresponding differences for the climate field valid in the middle of the month (CL), for the initial state for integration A (AI) and for the initial state for integration O (OI).

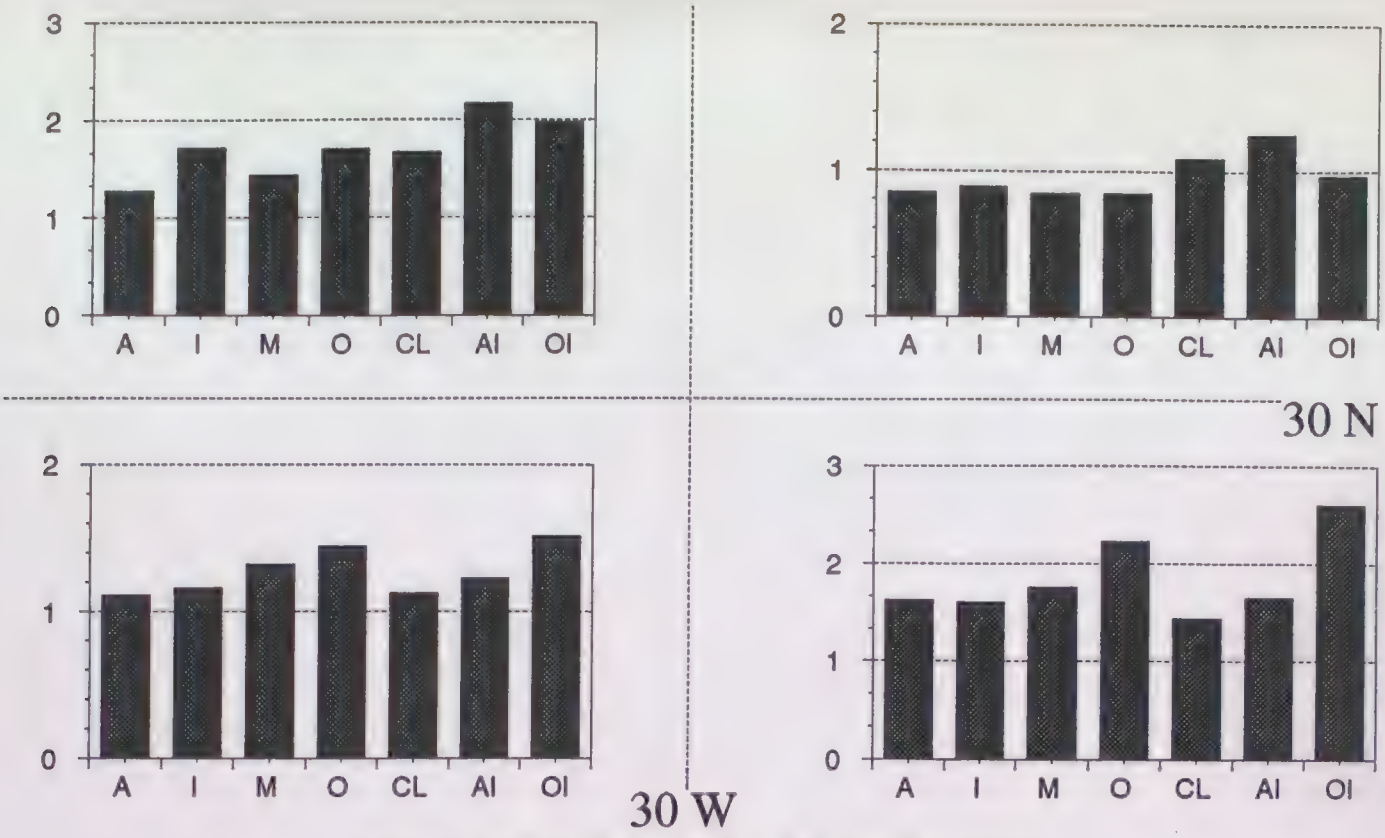
The main difference between integrations A, M and O is in their initial conditions. In each integration, prior to assimilation, the model is spun up from an initial condition of the Levitus potential temperature and salinity fields at rest. In integration A the spin up period was only 1 month, in M it was 1 year and in O it was 6 years.

Integration I is essentially the same as A except that during the assimilation the model's time

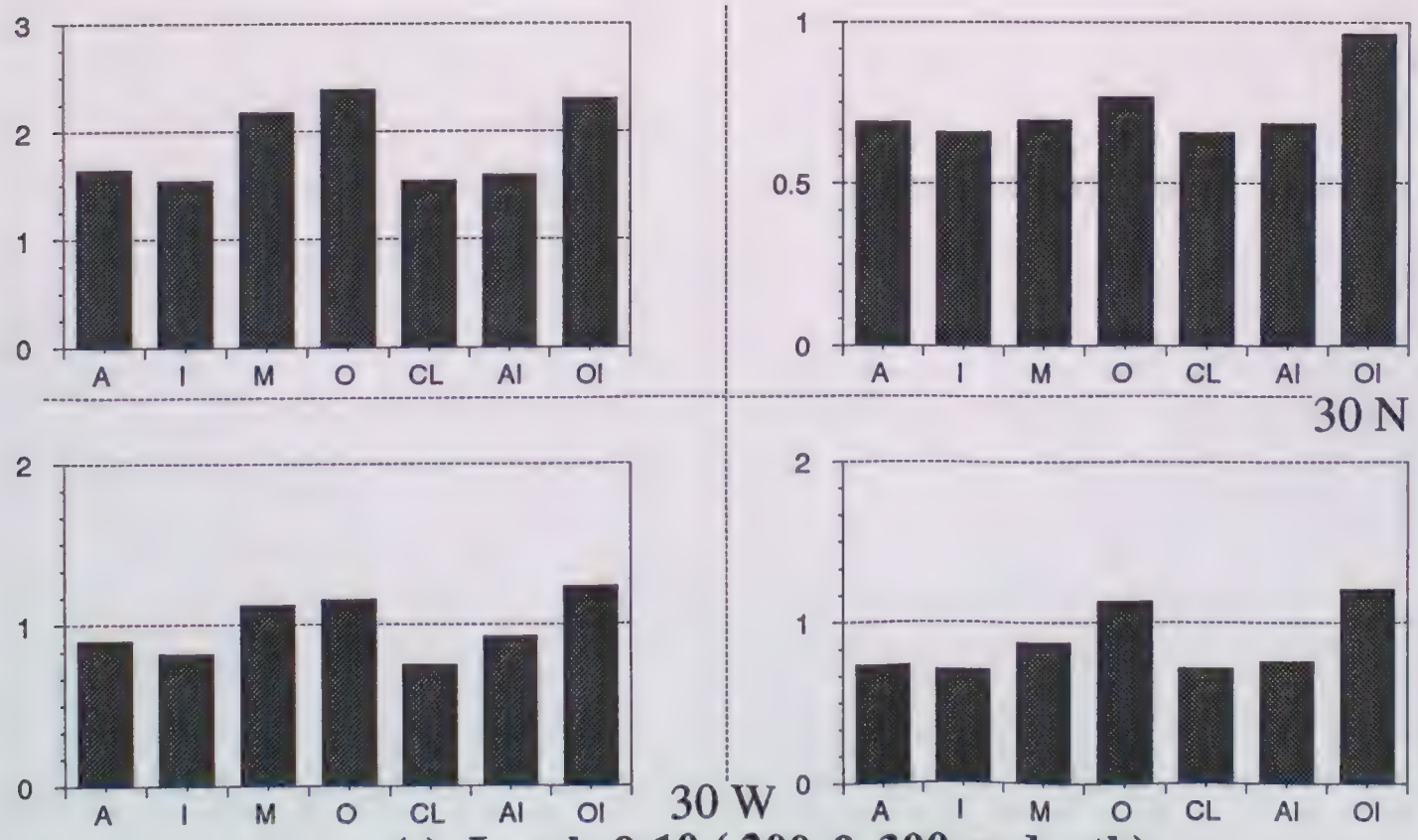


(a) Level 1 (5 m depth)

Figure 5 Root mean square differences for three sets of levels in each of four areas between fields output at the end of each of the (four) weeks in April and independent observations reported between 02 and 29 April 1993. The areas are divided by the 30°W line of latitude and 30°N line of longitude and the bar charts are plotted in the appropriate area. Units are °C.



(b) Levels 4-6 (35 - 67 m depth)



(c) Levels 9-10 (200 & 300 m depth)

steps are omitted; changes to the model state are due simply to the analysis increments based on the observational data.

The most immediately striking aspects of Figure 5 are:

At the surface:

a. the initial fields are worse than the climate field and the assimilated fields are always better than their initial fields.

b. except in the SW area the assimilations are better than climatology (or the initial conditions)

c. results for assimilations (which include model time steps) are better than the corresponding analyses (compare A and I).

Between 30 and 70 metres:

a. the initial fields are generally worse than climatology. OI is particularly poor in the areas south of 30 °N.

b. assimilations A and M are better than climatology in the areas north of 30 °N.

Between 200 and 300 metres:

a. climatology is as good as the best integration (which is I)

b. the climate field has smaller r.m.s. errors than the initial state for A which is much better than the initial state for O

c. assimilations (A) are slightly worse than corresponding analyses (I).

Because of the dependence of the statistics on the area covered it is not easy to make even crude comparisons with statistics for global areas or the Pacific. The closest comparisons can be made with Clancy et al. (1992) which presents results for February to April in 1988 and 1990 from analyses using bathy and surface temperature data. The main points are that their results at the surface are similar in that they improve on climatology in the North Atlantic (in areas north of 30 °N) but not in the areas south of 30 °N. At 300 metres however, their analyses do improve on climatology in all their areas of the Atlantic. We (the FOAM group) expect to use surface data in the near future. Thus the performance of our present system at the surface is of secondary interest. The poor performance at depths such as 50 metres is the main concern of this paper.

Additional integrations changing the weight given to the observations and the correlation scales used (see Bell 1994) showed that, except in the north west Atlantic, the system was surprisingly insensitive to these parameters and that problems with the model integrations

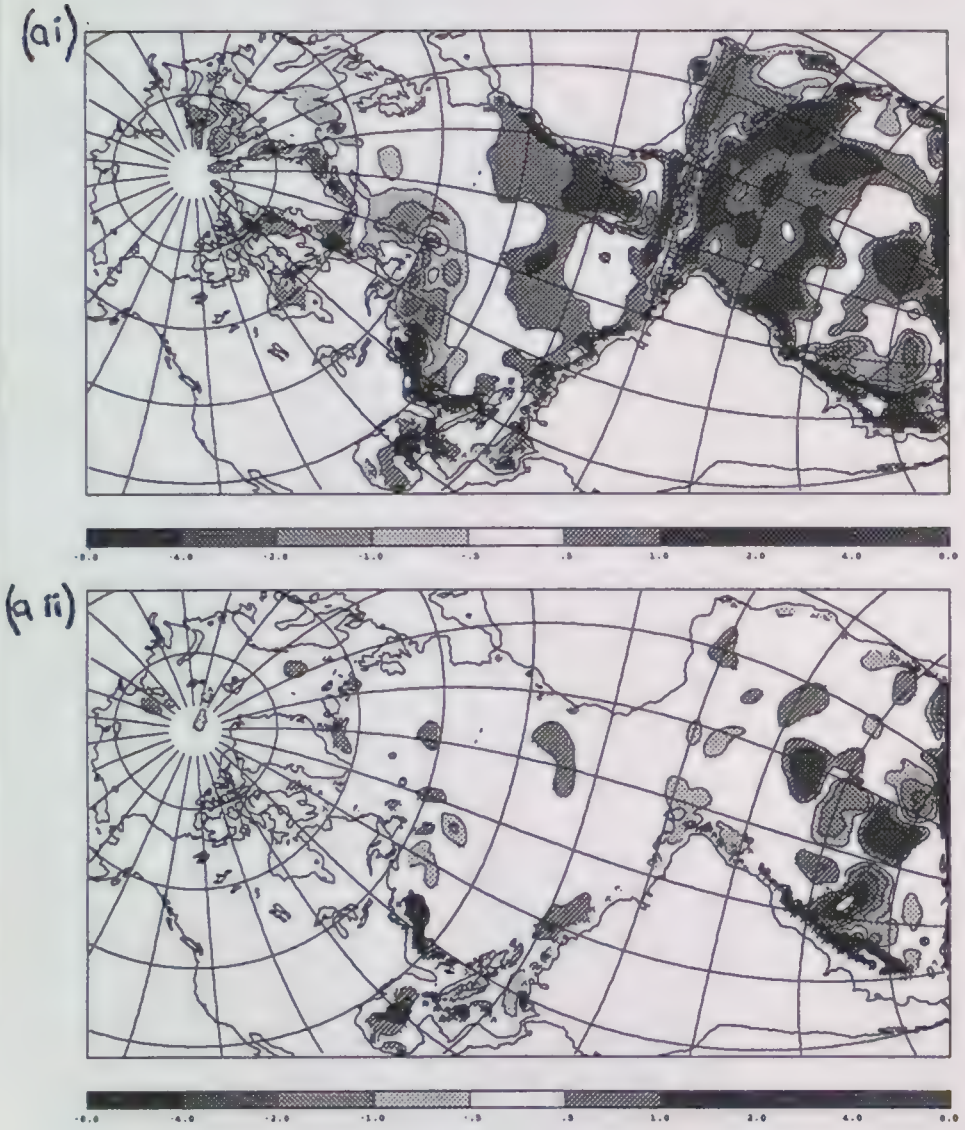
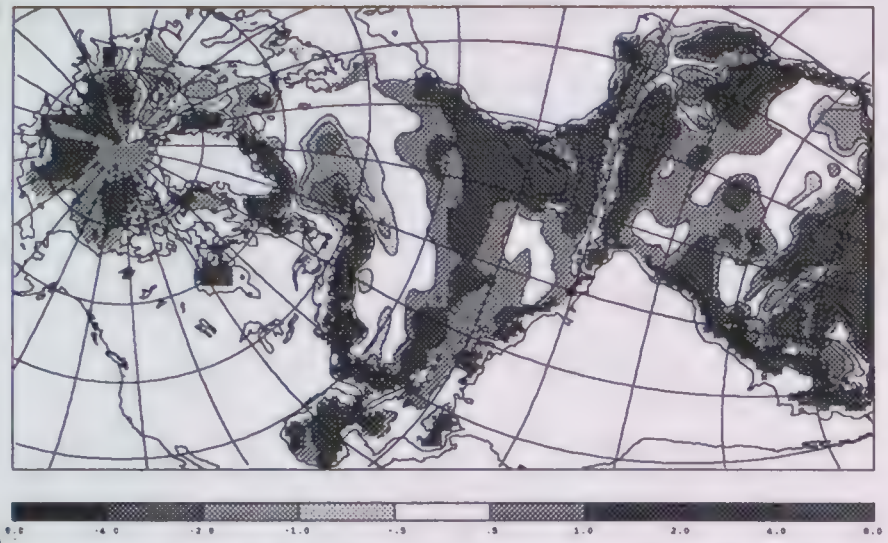


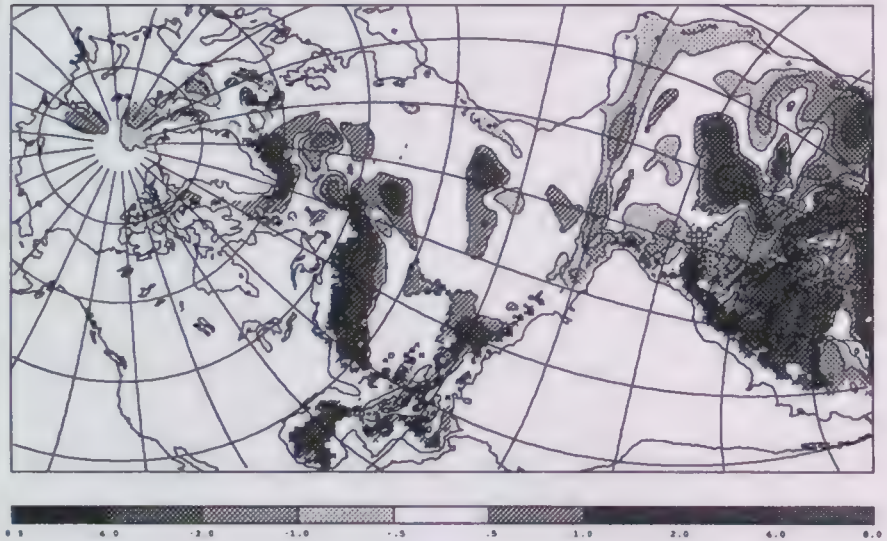
Figure 6 The differences between the the model and the Levitus climatology potential temperature fields at the end of April after (a) 1 month (b) 1 year and (c) 6 years of model integration. Fields in (i) are for level 5 (48 metres) and in (ii) are for level 10 (300 metres). Units are °C.

Figure 6 cont.

(bi)



(bii)



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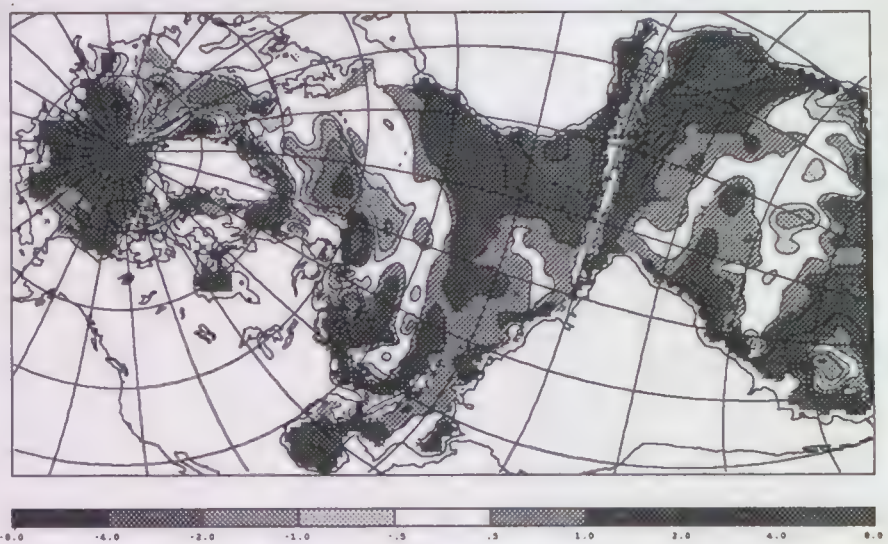
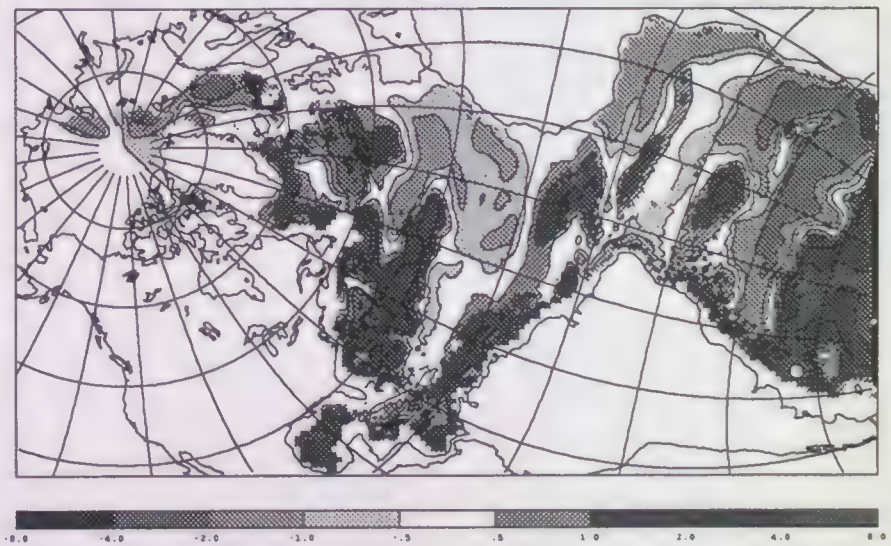


(cii)



were more important than fine tuning of these parameters at this stage.

3.3 Dependence on Model

The poor statistics for the initial state for integration O suggest that it is necessary to look at the evolution of the model bias during the 6 year spin up. The model potential temperature at the end of April minus that of climatology (for 30th April) is shown in Figure 6 at (i) 50 metres depth and (ii) 300 metres. The model field used in (a) is after a 1 month spin up, in (b) is after a one year spin up and in (c) is after a 6 year spin up. At 50 metres there is a rapid response of cooling at the equator on the eastern side of the basin, warming in most areas equatorward of 30 °N or °S and cooling of the North Atlantic drift. At 300 metres large biases develop quickly in the South Atlantic presumably because of the unrealistic no slip condition at the southern boundary. These will result in poor statistics in areas 3 and 4. So as not to contaminate the statistics in the areas south of 30 °N with these problems (which should not occur in a global model) the statistics in sub-section 3.5 only include data north of 15 °S. In the North Atlantic biases develop more slowly but after 6 years are larger than the model's annual cycle at this depth.

Fields from the model used in the above experiments contain grid point noise which is particularly strong around 300 metres depth at the edge of the subtropical gyres (where the thermocline is strongly sloped). Figure 7(a) illustrates the noise clearly. Over the area covered by each model grid box figure 7 displays the grid point's potential temperature value. The model mixes tracers much more strongly along than across isopycnals. Steve Foreman has determined how this can lead to the noise shown in Figure 7(a). There are various ways in which this noise can be avoided; Gent & McWilliams (1993) suggest an alternative method for "isopycnal" diffusion. As an interim measure I have changed from isopycnal to simple horizontal mixing of tracers. Figure 7(b) shows that this eliminates grid point noise in the potential temperature fields from our model.

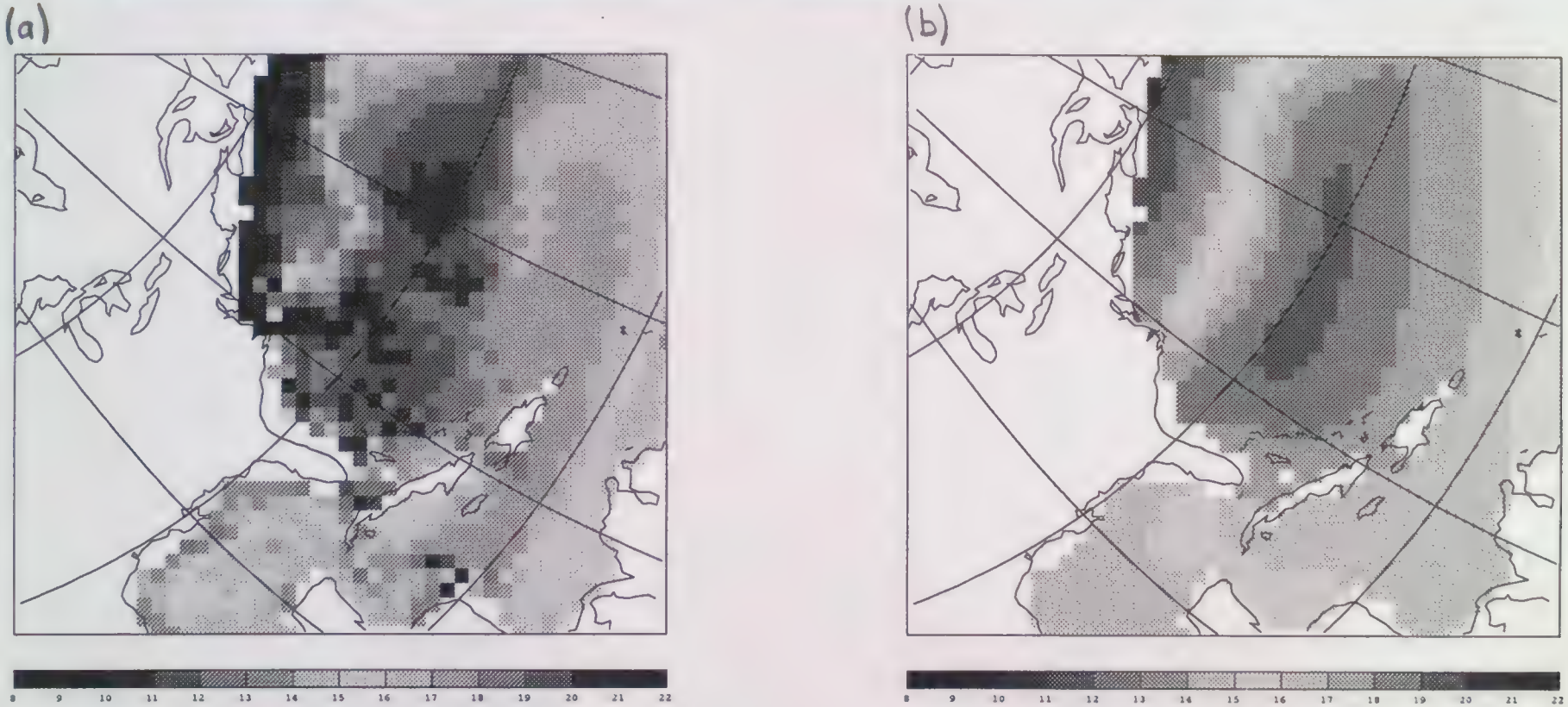
3.4 Impact of Deep Thermal Increments on Streamfunction

During January 1994, Oscar Alves drew attention to the unrealistic nature of the streamfunction after a few days of data assimilation in the near real-time runs. Figure 8 shows streamfunctions from the end of April for (a) the model spun up for just over 6 years to the end of April without data assimilation (i.e. the control run) and (b) integration O. The subtropical gyre circulation spun up by the wind stress is actually destroyed within 2 weeks of starting to assimilate data.

Oscar suggested that unrealistic thermal increments in the deep layers were responsible for the damage to the streamfunction. To find out if this were the case, I ran an integration T which was basically a repeat of O except that the observation weights were multiplied by 0.5 at level 12 (666 m) and by 0.0 at and below level 13 (995 m). Figure 8(c) which presents the streamfunction from this run at the end of April is much like that of the control (figure 8(b)).

The observations received from the GTS each month are probably not of sufficient quality

Figure 7 The potential temperature values in each grid box for fields at 300 metres depth for the end of April in (a) the model used in the assimilations of sub-section 3.2, which mixes tracers most strongly along isopycnal surfaces, after 6 years of integration and (b) a similar model, except that it mixes tracers mainly along horizontal surfaces, after 1 month of integration starting from the fields for the end of March (in the 6th year of integration) for the original model .



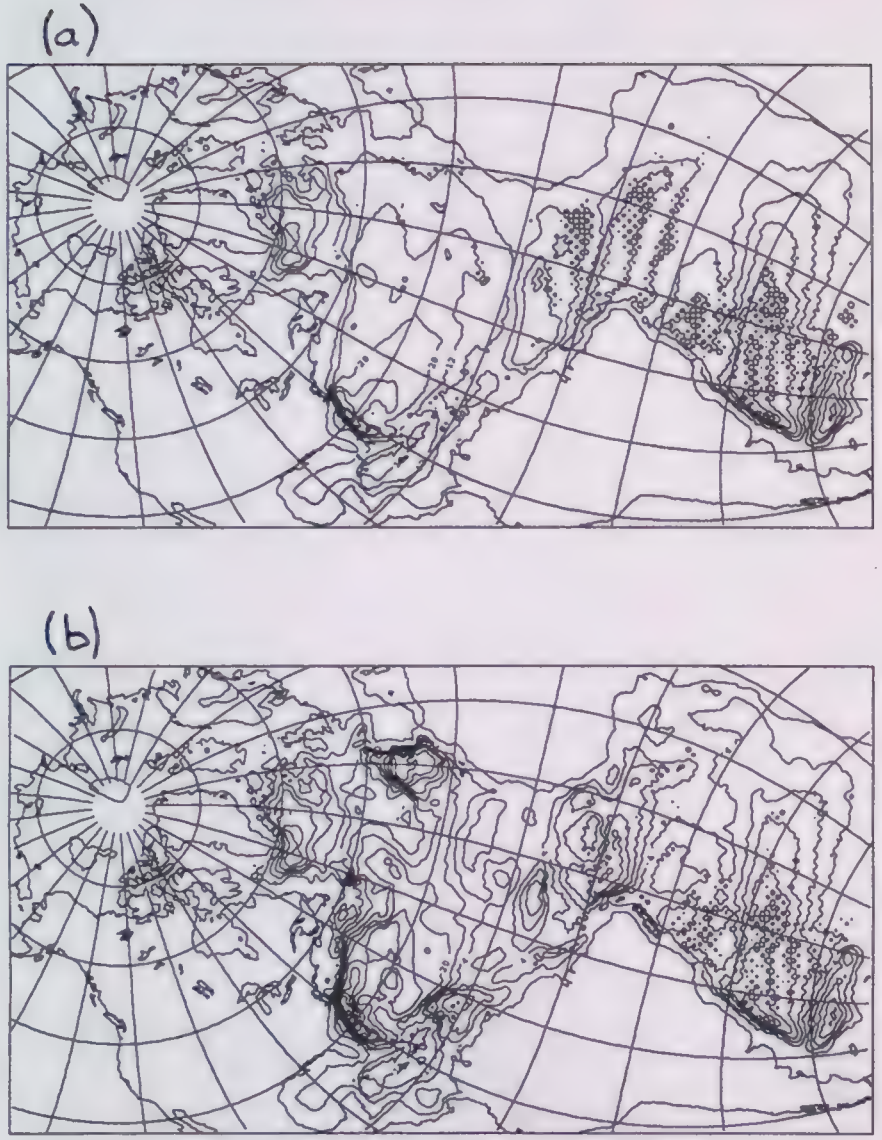


Figure 8 Streamfunctions at the end of April for (a) the control run for experiment O (b) experiment O and (c) experiment T. The streamfunctions are plotted in Sverdrups (10^6 m^3 s^{-1}) with a contour interval of 8.

or number to enable realistic assimilation increments to be made below level 12. The experiments described in sub-section 3.5 follow experiment T in not using observations below this level. They also spread the observation increments at higher levels much less strongly in the vertical than was done in the experiments described in 3.2.

3.5 Results from July-September experiments

As results from the one month assimilations were strongly influenced by the initial conditions I have performed a number of three month assimilations using data from July-September 1993. Three months should be a long enough period for improvements in fields due to aassimilation of data to become apparent.

As discussed in sub-sections 3.3 and 3.4 the integrations in this section differ from those in 3.2 in that

(i) the isopycnal mixing of tracers has been changed to purely horizontal mixing

(ii) observations are not used at or below 995 metres (level 13) and observations are spread less strongly in the vertical

(iii) observations south of 15 °S are not included in the statistical assessments.

The integrations started from model fields which had been spun up (as in sub-section 3.2) for only three months.

As some aspects of our quality control are unsatisfactory I have performed integrations with data gathered and quality controlled by Ants Leetmaa's group at NMC (Washington D.C.) as well as with data received at the Met. Office from the GTS in near real-time. This should help to indicate which aspects of the assimilation system need the most urgent attention.

The r.m.s. errors for the fit of the fields from the four weeks of September to independent observations from the following week are displayed in Figure 9 (c.f. figure 5). The top two letters in the names under each bar in the bar charts indicate how the fields were derived: CL denotes the climate field for the middle of September, CT the "control" model integration in which data is not assimilated; SG an aSsimilation using GTS data; LG an anaLysis using GTS data; SN an assimilation using NMC data; and LN an analysis using NMC data. The final letter indicates the source of the observations against which the field is compared; G indicates that GTS data and N that NMC data were used.

The main points arising from figure 9 are:

(i) Surface temperatures derived using the GTS data generally have smaller r.m.s. errors when compared to NMC data (SGN) than when compared to GTS data (SGG). This suggests that the NMC data is of bettter quality at the surface. Analyses and assimilations in areas north of 30 °N for level 1 and levels 4-6 using NMC data (LNN and SNN) have smaller

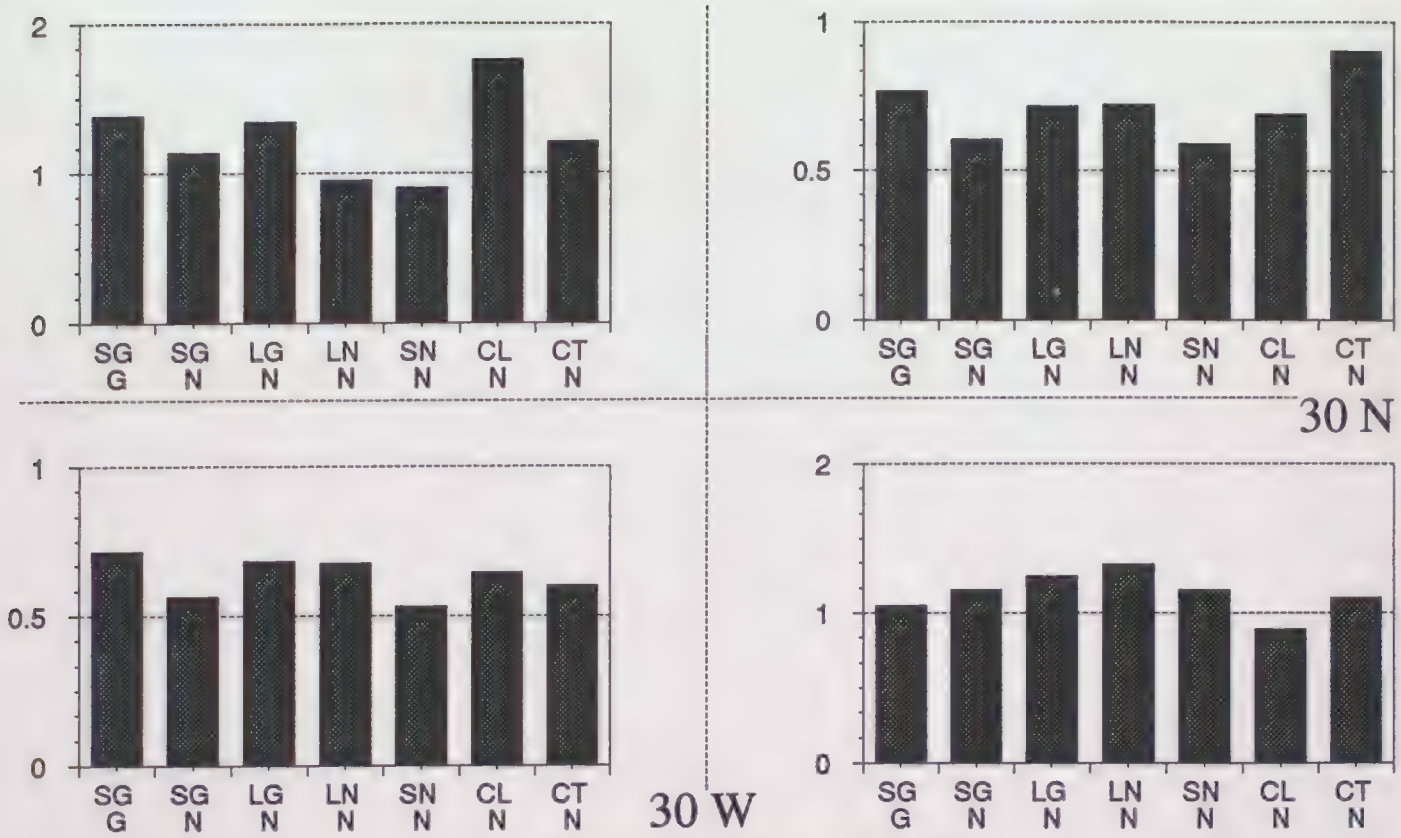
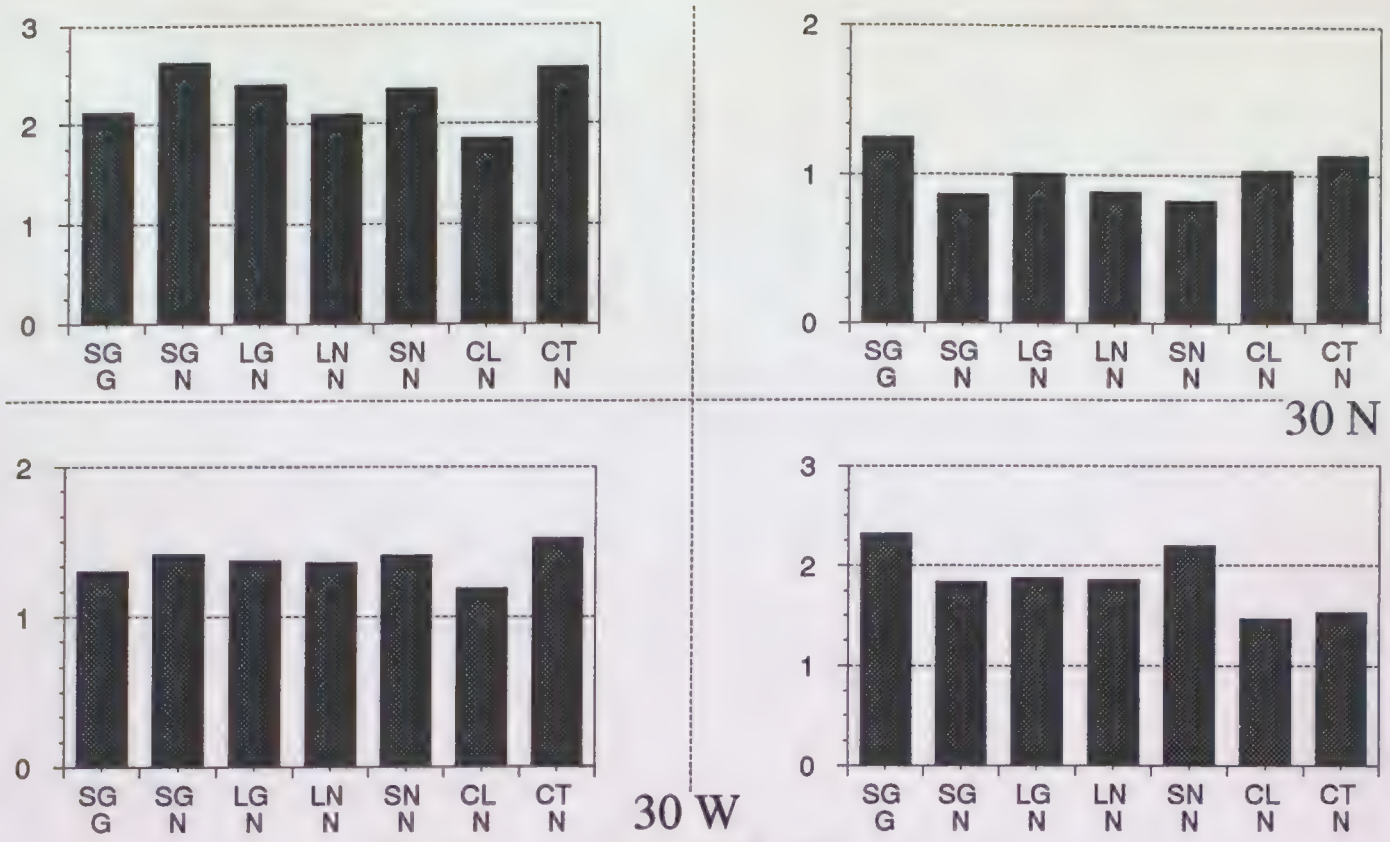
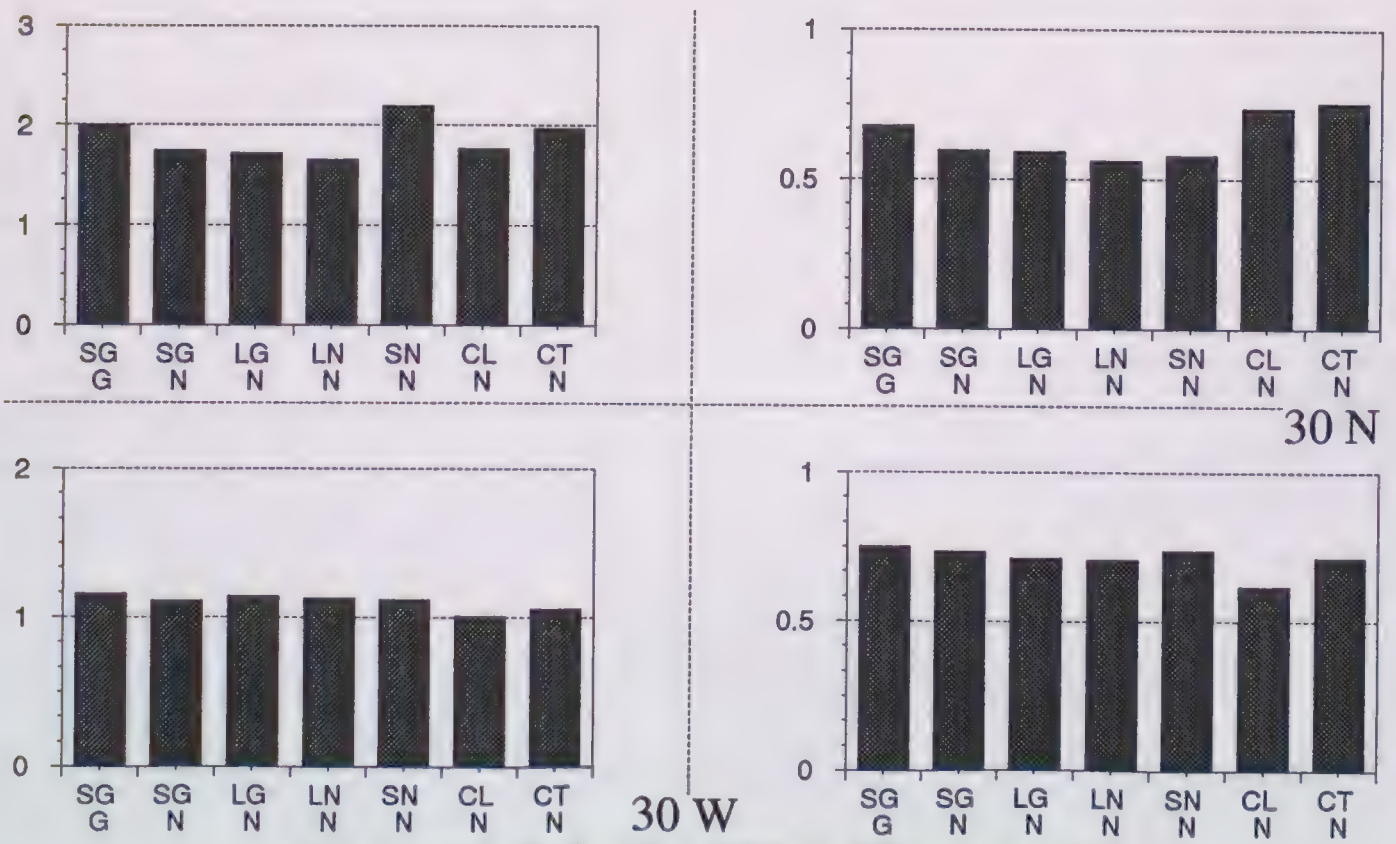


Figure 9 Root mean square differences for three sets of levels in each of four areas between fields output at the end of each of the (four) weeks in September and independent observations reported between 09 September and 06 October 1993. The areas are divided by the 30°W line of latitude and 30°N line of longitude and the bar charts are plotted in the appropriate area. Units are °C.



(b) Levels 4-6 (35-67 m depth)



(c) Levels 9 & 10 (200 & 300 m depth)

r.m.s. errors than those produced using GTS data (LNN and SNN). This improvement is not evident at levels 9 and 10 or south of 30 °N at any levels.

(ii) At the surface the assimilations are better than corresponding analyses (and initial conditions) and better than the climatology except in the SE area.

(iii) Climatology has smaller r.m.s. errors at lower levels than the control in most cases (particularly at levels 4,5 and 6).

(iv) The assimilations in the SE area have larger r.m.s. errors than the control and are no better than the analyses (particularly at levels 4,5 and 6).

The poor performance of the assimilations in the SE area is discussed in Bell (1994). The TOGA group at the Met. Office have found that their assimilations using the FOAM system in the equatorial Pacific are improved by spreading increments preferentially along lines of latitude near the equator (i.e. using anisotropic correlation scales).

Figure 10 provides an alternative comparison of the quality of (a) the assimilation and (b) the climate fields at 50 metre depth (level 5). It shows the difference of each of these fields from the control run for 15th September. It is clear that there are many similarities between the fields in the North Atlantic showing that the assimilation is pulling the model field towards the climate field over most of this area. This figure (and similar results for other months) and the fact that analyses are not greatly inferior to assimilations suggest that the poor quality of the model evolution is a serious handicap to the assimilation system and that a relaxation of the model towards climatology might improve the assimilation if the climatological increments were smoothed appropriately. The fields in figure 10 differ in the South Atlantic mainly in regions where there is no observational data and hence the assimilation and control are very similar.

4. Concluding Summary

Several tests of the present FOAM system, assimilating thermal profile data from April 1993 and July-September 1993 into a model of the Atlantic ocean, have been performed and assessed. Problems with grid point noise in the ocean model and undesirable responses of the streamfunction to data below 1000 metres depth have been identified and remedied. Generally speaking the assimilations have smaller r.m.s. errors in the potential temperature fields than the Levitus climatology at the surface but do not yet improve on climatology below 50 metres depth. This conclusion is true for the observational data received by the Met. Office directly from the GTS and for data compiled and quality controlled at NMC.

The FOAM group has now implemented a 1° x 1° global model and are assimilating thermal profile and surface temperature data into it. Surface fluxes from the Met. Office (and ECMWF) operational systems for each month in 1993 have been extracted and are now

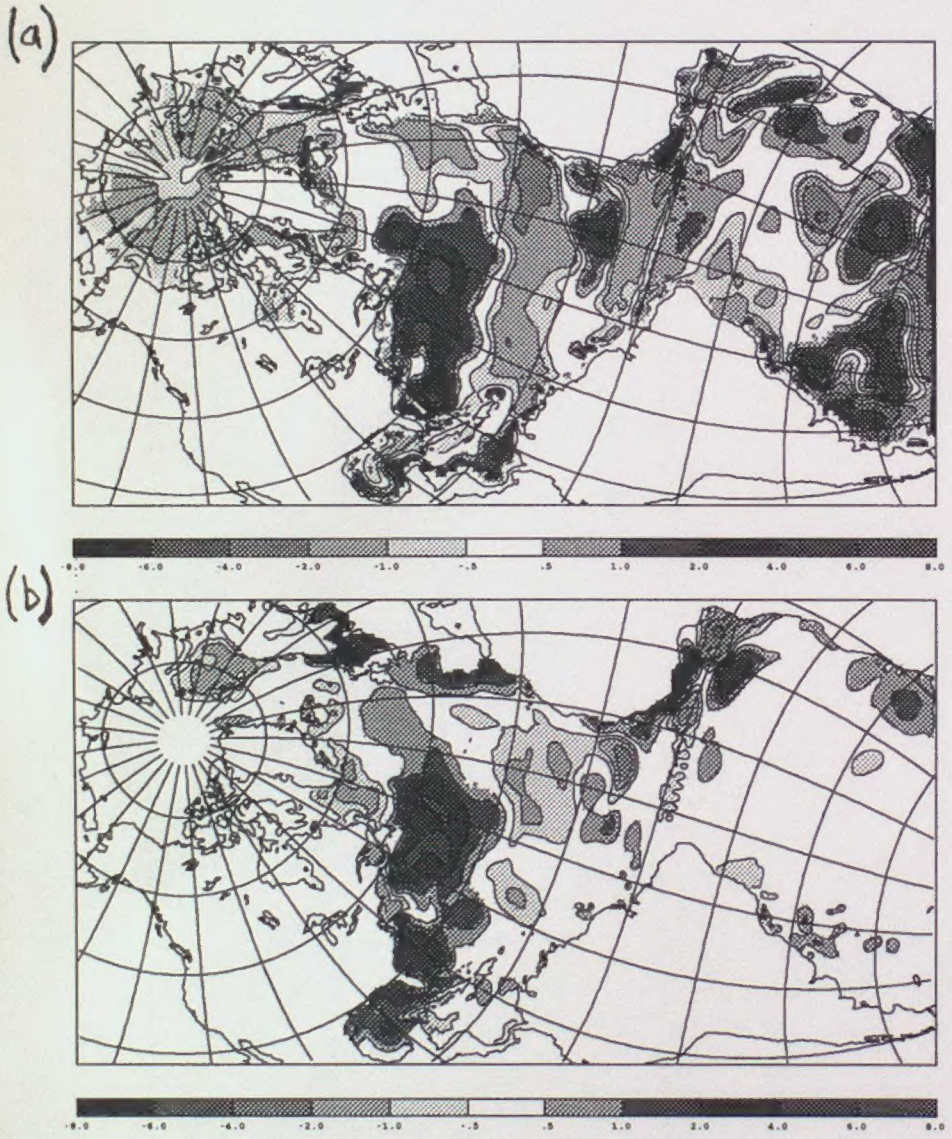


Figure 10 The difference from the control integration (no assimilation) at level 5 (48 metres) for the potential temperature fields on 15 September 1993 of (a) the climatology and (b) the integration into which NMC data has been assimilated. Units are °C.

available to drive this global model.

In future experiments we intend to improve the quality control of thermal profiles by using Levitus' estimates of standard deviations of observations from the climate mean values. We will also consider how to check for spikes and bulging in the XBT profiles. Anisotropic correlation scales will be used to improve assimilations in the equatorial belt. The model drift away from climatology will be examined further and integrations relaxing towards climatology tried if we consider such a relaxation is likely to be beneficial.

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